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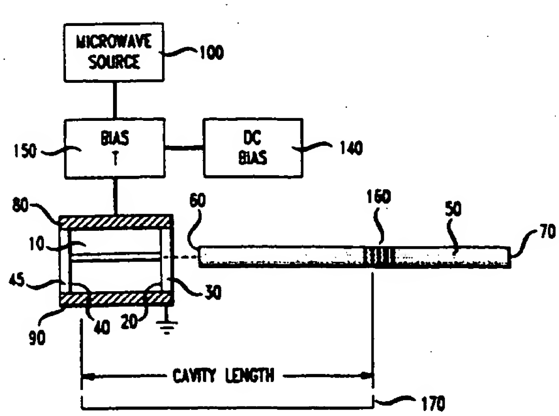
(54) **Compact laser optical source.**

(57) An optical source includes a semiconductor diode laser (10), an external optical cavity (170), and a source of drive current. The external cavity includes an optical fiber (50) and a distributed Bragg reflector (160). The distributed Bragg reflector is chirped. As a consequence, the optical source exhibits self-tuning behavior.

FIG. 1

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## Field of the Invention

This invention relates to optical systems of the kind in which a semiconductor diode laser has an optical cavity that is at least partially external to the diode structure.

## Art Background

For long-distance optical fiber communication, it is desirable to provide a source of transform-limited optical pulses which is compact, reliable and stable, and which operates at an appropriate wavelength and repetition rate. In particular, it is currently believed that for soliton-based communication, a wavelength of about 1.55 μm, a pulse width of 15 - 60 ps, and a repetition rate roughly in the range of 2.5 - 10 GHz are desirable. Actively mode-locked, semiconductor diode lasers are advantageously used as sources of optical pulses for such purposes. However, there are several problems associated with the conventional use of external air cavities for mode-locking. Such cavities generally require the use of bulk optics, a diffraction grating for wavelength control, and an etalon for bandwidth control. As a consequence, optical alignment is a complicated and difficult matter, and it is difficult to provide a cavity which is compact enough for general use in optical communication. As an alternative, monolithic mode-locked lasers have been proposed. Such lasers are described, for example, in P.A. Morton, et al., 'Monolithic hybrid mode-locked 1.3 μm semiconductor lasers', Appl. Phys. Lett. 56 (1990) 111 - 113. However, the small physical dimensions of such devices permit operation only at repetition rates which are relatively high, and generally greater than preferred maximum rates for purposes of data transmission. Moreover, some such devices lack adequate bandwidth control to produce relatively long pulses which are transform limited.

Although not generally useful for producing communication signals, continuously operated semiconductor diode lasers have ubiquitous applications. However, one common problem that has been encountered in the cw operation of these lasers is so-called 'mode beating noise', which causes the output power to fluctuate. For at least certain applications of these lasers, it is desirable to provide means for stabilizing the cw optical output.

## Summary of the Invention

Described herein is an optical source which is compact, stable, and reliable, and which, when used as a pulse source, can provide at least approximately transform-limited optical pulses at appropriate wavelengths, repetition rates, and pulse widths for soliton-based communication. (Soliton-based signal transmission is described, *e.g.*, in L.F. Mollenauer, et al., 'Demonstration of Error-Free Soliton Transmission at 2.5 Gigabits per Second over more than 14,000 km', Elect. Lett. 27, (1991) 2055.)

In a broad sense, the invention involves a semiconductor diode laser which has at least one output facet through which electromagnetic radiation of at least a given wavelength is emitted, an opposing facet, to be referred to as the 'back' facet, an external optical cavity, and means for applying an appropriate drive current to the laser such that the laser is actively mode-locked, or, alternatively, such that the laser has continuous output. The cavity is defined between the back facet and a distributed Bragg reflector (DBR) situated at a given length from the output facet. The external cavity is not an air cavity, but instead lies substantially within an otpical fiber. One end of the fiber is proximal, and optically coupled, to the output facet, and the fiber has at least one end distal the facet. The DBR is formed by spatially modulating the effective refractive index in a portion of the fiber intermediate the proximal and distal ends. (The effective refractive index is related to the propagation constant in the fiber, with respect to the propagating mode.) The effective refractive index is modulated in an appropriately doped core of an optical fiber by, *e.g.*, exposing the fiber core to electromagnetic radiation of an effective wavelength such that a physical change takes place. In contrast to the prior art, the DBR is quasiperiodic and has a local period that changes with position along the fiber.

## Brief Description of the Drawings

FIG. 1 is a schematic, block diagram of the inventive optical source, in one embodiment.

FIG. 2 is a schematic diagram of the inventive source in a currently preferred embodiment in which a substantial portion of the optical cavity lies within an optical fiber, and the DBR is formed in the fiber.

FIG. 3 is a typical noise power spectrum of a cw laser system of the prior art, of the kind that includes a semiconductor diode laser and an external optical cavity terminated by a DBR. Spectral peaks indicating mode-beating noise are clearly visible in the spectrum.

FIG. 4 is a graph of the effective lengths of two illustrative DBRs as functions of optical frequency. Curve A represents a DBR having an approximately linear chirp, and Curve B represents a DBR having a constant period.

## Detailed Description

A block diagram of an optical pulse source according to one aspect of the invention is shown in FIG. 1. Semiconductor diode laser 10 typically has a cleaved output facet 20 which is coated with antireflection coating 30. Laser 10 also typically includes

cleaved back facet 40, which is optionally coated with high-reflectivity coating 45, or, alternatively, is left uncoated in order to provide a second output useful, *e.g.*, for monitoring purposes. Waveguiding element 50 is optically coupled to facet 20 at proximal end 60, and optical pulses are extracted from element 50 at least at one distal end 70. The ac drive current for the laser is exemplarily delivered to the laser through contacts 80 and 90 from variable-frequency microwave source 100. A dc bias is provided from dc current source 140 by way of bias network 150.

A distributed Bragg reflector (DBR) 160 is defined in a portion of element 50 intermediate ends 60 and 70. In general, the DBR is formed by impressing a pattern of modulations of the effective refractive index of the waveguiding element. Specific embodiments will be discussed in greater detail below. Defined between facet 40 and DBR 160 is optical cavity 170. As is discussed below, the spatially distributed nature of the DBR results in an effective cavity length which depends, to a limited extent, upon the operating conditions of the pulse source.

Although various alternative semiconductor diode lasers are envisioned, we currently prefer to use a strained quantum well laser operating, *e.g.*, at about 1.55μm. Such lasers are well-known to practitioners in the art, and are described, *e.g.*, in T. Tanbun-Ek, et al., Appl. Phys. Lett. 57, (1990) 2184.

Associated with the optical cavity is a round-trip time for optical pulses propagating therewithin. The multiplicative inverse of such round-trip time is referred to as the 'fundamental cavity frequency'. The laser is actively mode-locked by modulating the drive current at frequencies close to the fundamental cavity frequency.

It is generally believed that the performance of a mode-locked laser is very sensitive to the modulation frequency. In particular, the pulse width and the time-bandwidth product are generally believed to increase steeply as the modulation frequency is detuned away from the optimal frequency. However, we have discovered that the inventive optical pulse source has a surprisingly broad useful range of modulation frequencies. For example, in experiments, we have measured pulse widths of about 55 ps together with a time-bandwidth product of less than 0.5 over a bandwidth greater than 60 MHz, centered on a frequency of about 3.875 GHz. According to our current understanding, this effect is attributable to the spatially distributed nature of the Bragg reflector. That is, the distance to the effective reflection position within the reflector depends on wavelength. It is shortest at the Bragg wavelength, and increases for wavelengths both longer and shorter than the Bragg wavelength. As a consequence, the effective length of the optical cavity may vary as the operating wavelength is varied. If the modulation frequency is changed, the center wavelength of the output spectrum shifts, and concomitantly, the effective cavity length also changes. Through such changes in the effective cavity length, the optical pulse source tends to self-adjust in such a way that resonance is maintained. For example, we have observed, in an experimental optical pulse source, a center wavelength of 1.5475 μm at modulation frequencies above 4.1 GHz. That is the same wavelength that the experimental device exhibited under dc operation. However, reducing the modulation frequency below 4.1 GHz caused the center wavelength to decrease. We observed a maximum wavelength shift of over 1 Å for a modulation frequency change of 300 MHz.

In a currently preferred embodiment, the waveguiding element is an optical fiber. A substantial portion of the optical cavity, typically about 80% or more of the total optical length of the cavity, lies within the optical fiber. Turning now to FIG. 2, such an optical fiber 200 includes a lensed end 210 through which it is optically coupled to laser 10. Lensed optical fibers are well-known in the art, and are described, for example, in U.S. Patent No. 4,469,554, issued to D.R. Turner on September 4, 1984, and in U.S. Patent No. 4,932,989, issued to H.M. Presby on June 12, 1990. The lensed portion may be formed in a separate fiber stub, which is then readily attached to a distal fiber portion by means of fusion splice 220. However, it is preferable to avoid including a splice within the optical cavity, because such splices introduce optical loss, and tend to complicate the precise determination of the optical cavity length. The length of the optical cavity is primarily determined by the positioning of the grating. For that reason, it is desirable to position the grating with an accuracy of one millimeter or better, and preferable to position it with an accuracy of a few tenths of a millimeter. Such accuracy is readily achievable by a skilled practitioner.

In at least some cases, an optical isolator 230 is advantageously incorporated at a point distal DBR 240 for the purpose of preventing transmitted electromagnetic radiation from reflecting back into the laser.

DBR 240 is typically formed by a photoinduced effect. That is, a permanent alteration in the refractive index of at least some silica-based glasses is effected by exposure to electromagnetic radiation, such as ultraviolet radiation. For example, such alterations are readily made in a silica fiber having a germanium-doped core by exposure to radiation of wavelength 242 nm from, e.g., an excimer-pumped, frequency-doubled, tunable, dye laser. (One commercially available optical fiber which is useful in that regard is manufactured by AT&T under the tradename ACCUTETHER 220.) In an optical interferometric arrangement, a series of interference fringes of radiation of the effective wavelength is readily produced with a periodicity appropriate for the DBR. The DBR is formed by exposure of an optical fiber to such an interference pattern. This technique is well-known in

the art, and is described, for example, in U.S. Patent No. 4,725,110, issued to W.H. Glenn, et al., on Feb. 16, 1988. An external cavity laser which uses such a DBR, but is not mode-locked, is described in D.M. Bird, et al., 'Narrow Line Semiconductor Laser Using Fibre Grating', Electr. Lett. 27 (1991) 1115-1116.

Example 1

An optical pulse source having an optical fiber cavity was made substantially as described above. A single-mode fiber having a germanium-doped core and a lensed end was used. The cavity length was about 40 mm. The DBR was photoinduced substantially as described. The Bragg wavelength was 1.5328 μm. The measured reflectivity of the DBR had a peak value of 63% and a full width at half-maximum (FWHM) of 2.0 Å. The physical length of the DBR (FWHM) was 5 mm.

Active mode locking was performed at the optimal modulation frequency of 2.37 GHz and a bias level of 36 mA. The ac drive current was provided by delivering a signal, at a power level somewhat less than one watt, from a high-power, sinusoidal microwave source into a step recovery diode to produce an inverted, short-pulse waveform. The diode output was sent through an inverter to produce positive pulses, and the inverter output was applied to the laser.

Mode-locked pulses were obtained having a full width at half-maximum of 18.5 ps, an optical bandwidth of 1.3 Å (i.e., 16.7 GHz), and a time-bandwidth product of 0.31, which is at the transform limit for a sech-squared pulse shape. The threshold current of the laser was 11 milliamperes, and the peak optical power output was 49 mW.

We have found that the inventive pulse source can exhibit self-tuning behavior. That is, the fundamental cavity frequency is inversely proportional to the effective optical length of the cavity. This length, in turn, depends on the operating wavelength. If the DBR has a constant period (i.e., the DBR is not chirped), the effective optical length will be somewhat longer for wavelengths slightly longer or shorter than the design wavelength of the DBR. The self-tuning behavior is observed when the modulation frequency is slightly lower than the fundamental cavity frequency corresponding to the design wavelength. In such cases, the operating wavelength may spontaneously increase or decrease by a small amount. As a consequence, the effective optical length of the cavity is increased, the fundamental cavity frequency is reduced to roughly the same value as the modulation frequency, and mode-locking is preserved.

However, because the self-tuned device will have a choice of two possible operating wavelengths, the optical output spectrum can exhibit instabilities. For example, we have observed, in some cases, a twin-lobed optical spectrum.

These instabilities can be avoided by using a DBR which does not behave symmetrically relative to wavelengths that lie, respectively, above and below the design wavelength. For example, a linearly chirped DBR can be used to assure that only one operating wavelength will correspond to a given modulation frequency. In the chirped DBR, the Bragg condition will be satisfied only in a short segment of the grating. The longitudinal position of that segment will depend on the operating wavelength. In a rough sense, each possible operating wavelength will be reflected from a segment situated at a unique one of these longitudinal positions. Each of these positions will correspond to a unique value of the fundamental cavity frequency. At a given modulation frequency, the laser will self-tune by adopting that operating wavelength that gives a fundamental cavity frequency matched to the modulation frequency.

By using a relatively long, chirped reflector, it is possible to accommodate relatively large changes in modulation frequency while preserving mode-locked operation. This is quite surprising for a mode-locked laser system. For example, we were able to mode-lock a device similar to that described above over a frequency range of 2.1 - 2.8 GHz. Over this 700-MHz range, the center wavelength of the device varied by 3 Å.

It should be noted in this regard that chirped gratings are useful not only for stabilizing the operation of mode-locked lasers, but also for stabilizing continuously operating (cw) diode lasers. That is, the laser cavity is generally able to support a multiplicity of closely spaced, Fabry-Perot resonant modes. Ideally, only one of these modes experiences maximum gain, and the light emitted by a cw laser corresponds exclusively to this mode. However, it often happens in practice that substantial emission occurs in more than one mode. One undesirable consequence of this is so-called 'mode-beating noise', which causes the output optical power to fluctuate. Surprisingly, we have found that in at least some cases of continuous operation of laser 10, chirping of the DBR will reduce mode-beating noise below detectable limits.

FIG. 3 is the noise power spectrum of the continuous optical emission from a laser system as described above, including a DBR having a constant period. Peaks at numerous, uniformly spaced beat frequencies are clearly visible. When we substituted a DBR having an approximately linear chirp, these peaks were completely eliminated. The chirped DBR was oriented such that the local Bragg wavelength was largest at the end proximal the diode laser, and smallest at the distal end. (In some cases, the reverse orientation may also be effective.) The strength of the DBR (i.e., the magnitude of the quasiperiodic refractive index perturbations) was smallest near the ends, and greatest near the center, and had an approximately Gaussian profile. The effective length of this

DBR is shown in FIG. 4 as a function of optical frequency. In the figure, Curve A represents the chirped DBR, and Curve B represents a typical DBR having a constant period. The optical frequencies of FIG. 4 are referred to the wavelength of maximum reflectivity of a hypothetical DBR whose background refractive index is unaffected by the perturbations. (In a real DBR, the spatial average of these perturbations contributes to the effective background index. Often, this background contribution has a Gaussian profile, which may add a small quadratic component to the total chirp of the DBR.)

## Claims

1. Apparatus comprising:
   a) a semiconductor diode laser (10) having a back facet (40) and opposing the back facet (20) at least one output facet through which electromagnetic radiation is emitted;
   b) an optical fiber (50) situated adjacent and external to the laser and having an end (60) proximal and optically coupled to the output facet, the optical fiber including a distributed Bragg reflector (160), to be referred to as a 'DBR', situated a given length from the output facet such that an optical cavity (170) is defined between the back facet and the DBR with respect to the emitted electromagnetic radiation; and
   c) means (100) for applying a modulated drive current to the laser at an appropriate modulation frequency for actively mode-locking the laser such that optical pulses having approximately a given wavelength are emitted from the laser,
   CHARACTERIZED IN THAT
   d) the DBR is quasiperiodic and has a local period that changes linearly with position along the optical fiber such that the laser can self-tune by adopting an operating wavelength that gives a fundamental cavity frequency matched to the modulation frequency.

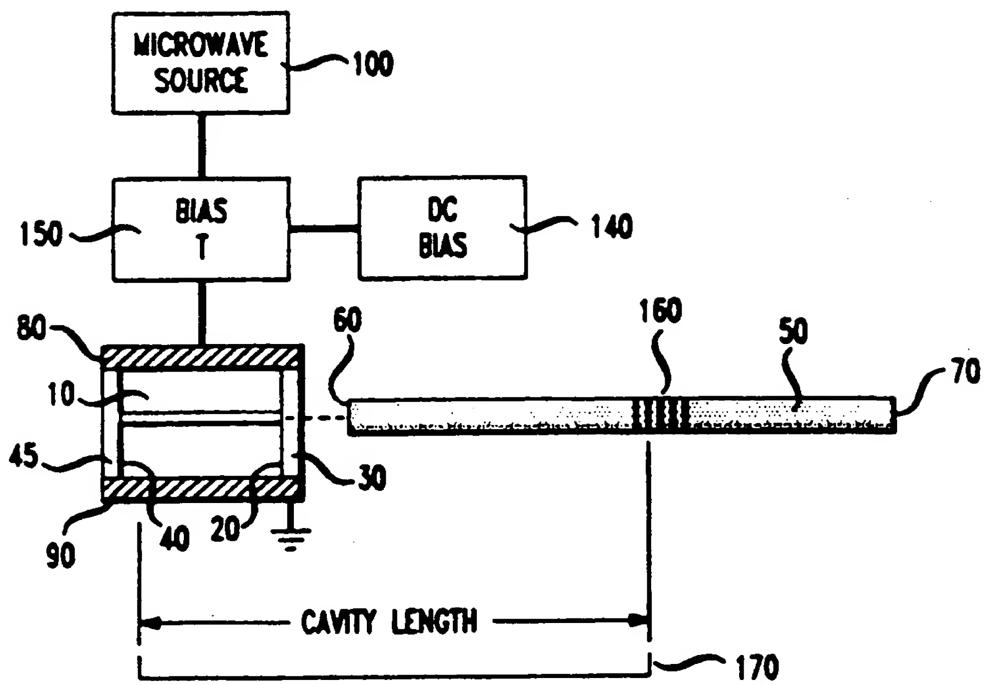
2. Apparatus comprising:
   a) a semiconductor diode laser (10) having a back facet (40) and, opposing the back facet, at least one output facet (20) through which electromagnetic radiation is emitted;
   b) an optical fiber (50) situated adjacent and external to the laser and having an end (60) proximal and optically coupled to the output facet, the optical fiber including a distributed Bragg reflector (160), to be referred to as a 'DBR', situated a given length from the output facet such that an optical cavity is defined between the back facet and the DBR with respect to the emitted electromagnetic radiation; and
   c) means for applying a drive current to the laser such that the laser has continuous optical output,
   CHARACTERIZED IN THAT
   d) the DBR is quasiperiodic and has a local period that changes monotonically with position along the optical fiber.

3. Apparatus of claim 2, wherein the local period changes approximately linearly with position along the optical fiber.

4. Apparatus of claim 2, wherein the local period changes such that continuous operation of the laser is substantially confined to one mode of the optical cavity.

5. Apparatus of claim 2, wherein the local period changes such that mode-beating noise is substantially eliminated from the optical output of the laser during continuous operation of the laser.

FIG. 1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100
BIAS T
150
DC BIAS
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80
10
45
90
40
20
30
60
160
50
70
CAVITY LENGTH
170

FIG. 2

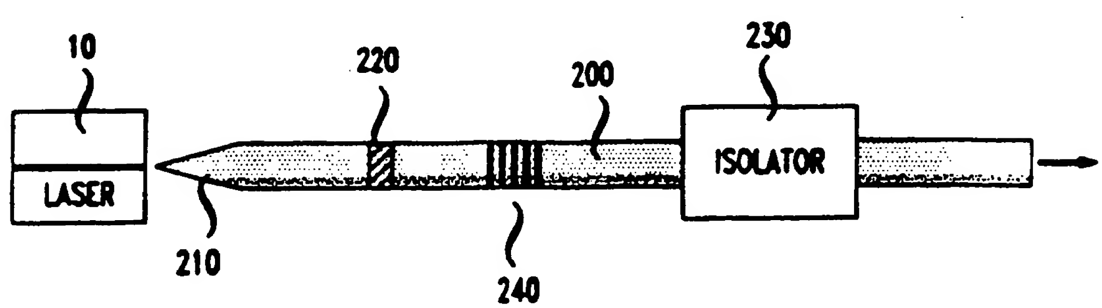
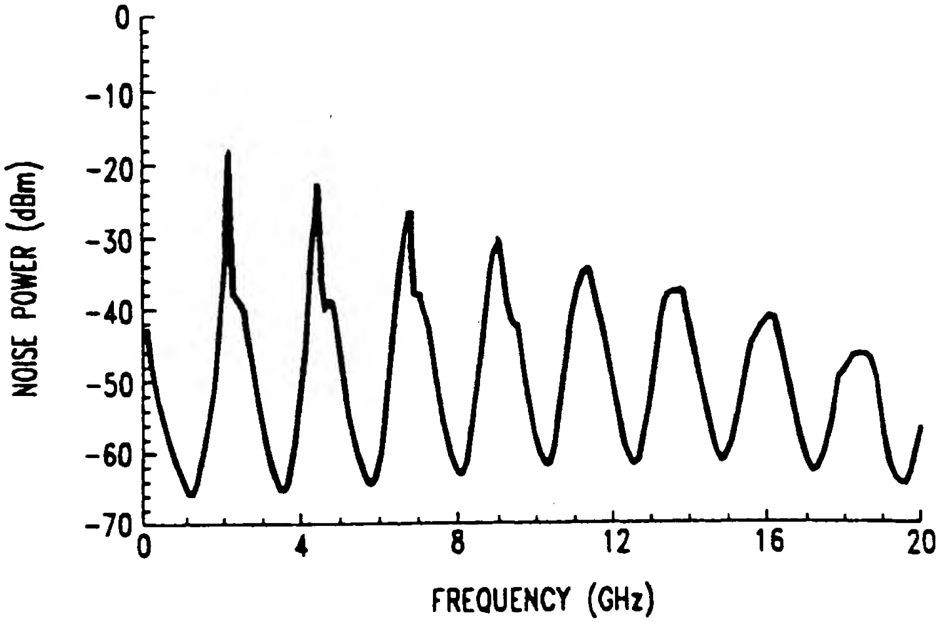

10
LASER
210
220
240
200
230
ISOLATOR

*FIG.* 3


0
-10
-20
-30
-40
-50
-60
-70
NOISE POWER (dBm)
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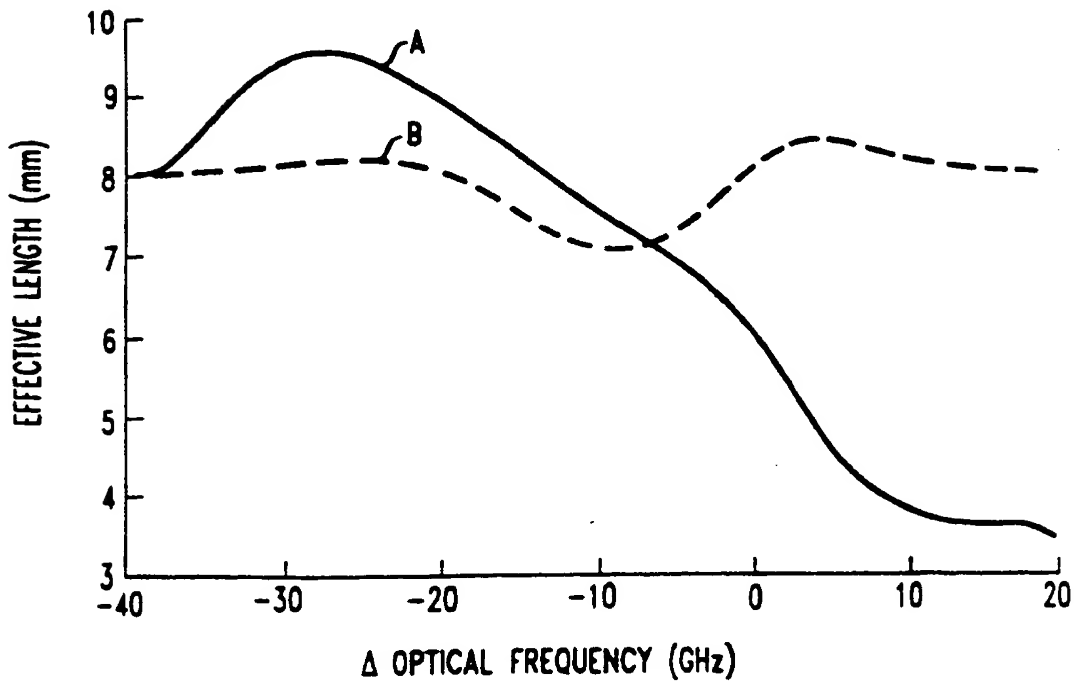
4
8
12
16
20
FREQUENCY (GHz)

*FIG.* 4


10
9
8
7
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5
4
3
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-30
-20
-10
0
10
20
Δ OPTICAL FREQUENCY (GHz)